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Western Regional Research Laboratory
Albany 6, California

# TUNNEL-AND-TRUCK DEHYDRATORS, AS USED FOR DEHYDRATING VEGETABLES

(A revision of the section entitled "Tunnel-and-Truck Dehydrators" in U. S. D. A. Miscellaneous Publication No. 540, "Vegetable and Fruit Dehydration, a Manual for Plant Operators", June, 1944.)

W. B. Van Arsdel

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## TUNNEL-AND-TRUCK DEHYDRATORS

The class of dehydrator which has been, by far, the most widely used for vegetable dehydration, both in the United States and in the British Commonwealth countries, may be called the "tunnel-and-truck" type. Another name is "truck-and-tray". Most commonly it is simply called the "tunnel" dehydrator, although that term might be applied justly to some other types as well.

The distinguishing characteristic of the class is the following method of handling: the prepared material is spread thinly on trays at the preparation line; the loaded trays are then placed one above another on a wheeled low truck or dolly to form a stack some six or seven feet high, a clear air passage being left between successive trays; loaded trucks are then placed one at a time in one end of the dehydrator, the drying section of which is a straight passage just large enough in cross-section to accommodate the loaded trucks. This "tunnel" may hold anywhere from as few as four to as many as fifteen or twenty trucks. In operation, a dried truckload is removed from the far end of the tunnel, the entire string of trucks is moved along one step, and the new wet truckload is inserted in the vacant space thus left. Introduction of wet material into the drier is therefore not steady and continuous, but is done periodically. This is known as "progressive" operation, to be contrasted with the continuous operation of most conveyor dehydrators, and flow of the drying air is primarily across the horizontal surface of the thin layer of wet material on the trays, not primarily through the wet layer as it is in most conveyor dehydrators.

Three basic arrangements of the tunnel-and-truck dehydrator have been used commercially, as well as several different combinations of two different arrangements in a single drying unit. The arrangements differ from one another in the direction of flow of the drying air relative to the direction of progression of the trucks. Simplified diagrams of the three basic types are shown in Figures 1 to 3. In the counterflow tunnel (Figure 1), drying air is introduced at the dry end of the tunnel, and moves straight through it in a direction opposite to that of the truck progression. In the parallel-flow tunnel (Figure 2), the air moves straight through the tunnel in the same direction as that of the truck progression.1/ In the combination compartment and tunnel (Figure 3) the drying air moves through the trucks transversely to the axis of the tunnel. The lateral bays in which the air stream is turned 180° between successive trucks may contain auxiliary heaters (as shown) and auxiliary blowers. In practice, all three of these types become more complicated through provisions for recirculating a part of the drying air.

The characteristics of counterflow, parallel-flow, and compartment tunnels, as well as of two-stage combinations of parallel-flow and counterflow tunnels, are described in the paragraphs which follow.

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1/ In the British Commonwealth countries this is usually called the "concurrent" arrangement, instead of "parallel-flow".

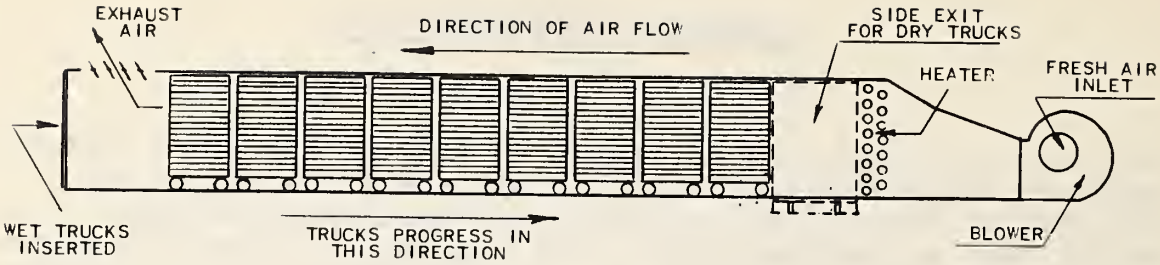


Figure 1. Simple counterflow tunnel (elevation).

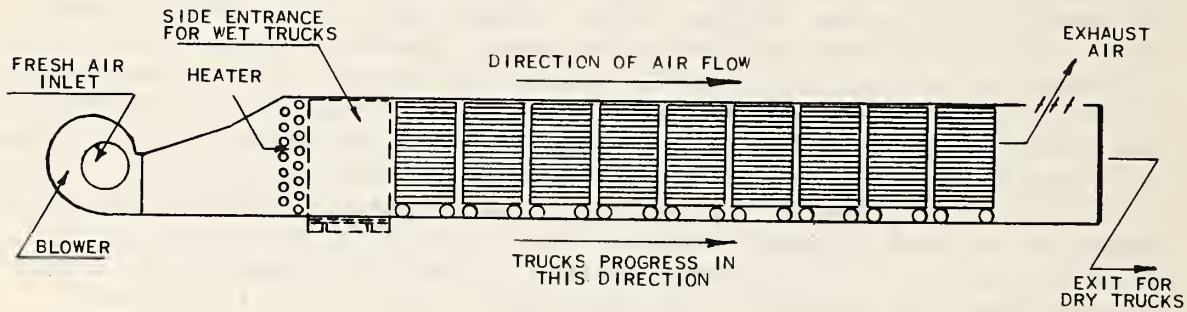


Figure 2. Simple parallel-flow tunnel (elevation).

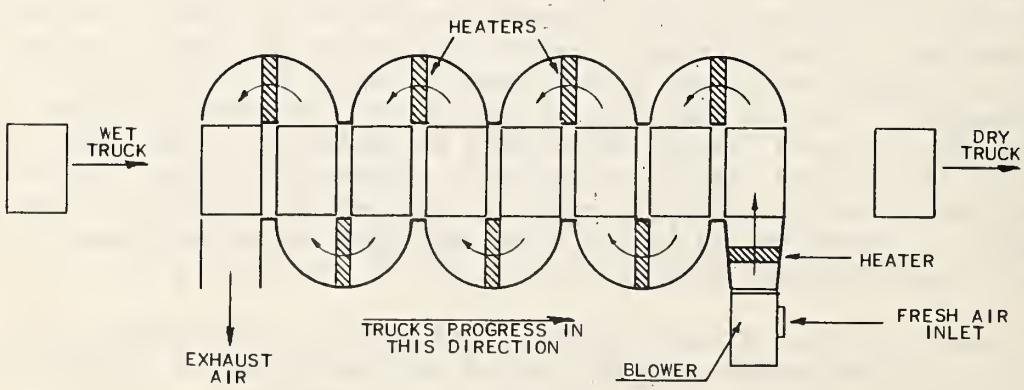


Figure 3. Simple combination compartment and tunnel (plan view).

## The Counterflow Tunnel

Counterflow tunnel dehydrators, of relatively simple design, account for most of the currently active fruit dehydration capacity, and a substantial proportion of the dehydrated vegetable production as well. The basic soundness of the design is attested by the fact that despite intensive investigation and development of dehydrators during the war years, no radical changes either in design or in mode of operation of the counterflow tunnel were found to be necessary.

Development of the counterflow tunnel in substantially its modern form must be credited largely to workers at the University of California and engineers and builders associated with them, particularly G. B. Ridley, W. V. Cruess, and A. W. Christie.2/ Untimely rains in 1918 and 1919 had caused the loss of a major part of the sun-dried prune crops of those years. The University group carried out extensive pilot-scale drying tests, adapted and simplified the designs of numerous pioneer workers in the field of fruit dehydration, and assisted builders to install well engineered driers throughout most of the prune drying area. Almost simultaneously with this development in California, workers at the Oregon State Agricultural Experiment Station, with the cooperation of the Bureau of Chemistry, U. S. Department of Agriculture, introduced somewhat similar units into the dried fruit areas of Oregon and Washington. Several plants, also using counterflow tunnels, were also built in California to produce dehydrated onions, garlic, peppers, and smaller amounts of miscellaneous vegetables.

When Army and Lend-Lease requirements for dehydrated vegetables rose sharply in 1941, a survey of existing dehydration plants disclosed a considerable number which could be adapted to the new operation.3/ At the same time, however, certain consequences of the nature of the prune-drying business imposed limitations. Many of the prune dehydrators were essentially farm units, meant to be operated by the owner of a single orchard with little outside help; they were too small to be economic in a vegetable operation. The fact that prunes are dried whole made it necessary to employ a 24-30 hour drying time, even though the desired final moisture content was only slightly below 18 percent; the tunnels were therefore built long (some of them held as many as 30 3-ft. x 6-ft. trucks) and the trays were loaded heavily. Even so, the rate of moisture evaporation from the entire tunnel was relatively low. The low

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2/ G. B. Ridley. Tunnel dryers. Ind. Eng. Chem. 13(5):453-460 (1921).
W. V. Cruess and A. W. Christie. Dehydration of fruits. Calif. Agr. Exp. Sta. Bull. No. 330, Sept. 1921.
W. V. Cruess and A. W. Christie. Some factors of dehydrater efficiency. Calif. Agr. Exp. Sta. Bull. No. 337, Nov. 1921.
A. W. Christie and G. B. Ridley. Construction of farm dehydraters in California. J. Am. Soc. Ht. Vent. Eng., Dec. 1923.
A. W. Christie. The dehydration of prunes. Calif. Agr. Exp. Sta. Bull. No. 404, Aug. 1926; revised by P. F. Nichols, Dec. 1929.
3/ Several of these plants operated successfully throughout the war.

profit margin and highly competitive nature of the business, combined with the shortness of the drying season, made it necessary to economize on power and fuel and to keep the capital investment small. These prune dehydrators therefore generally employed rather small blowers or fans, were arranged to permit recirculation of a large proportion of the air, and were able to operate with a relatively small heating unit.4/ A wet-bulb temperature of 100°-110° F. in the tunnel had no adverse effect on the quality of the prunes, and was believed to prevent cracking of the skins due to "case-hardening", with consequent loss of juice from the fruit.

Some of the basic conditions were entirely different when the material to be dried was diced potatoes or carrots, or shredded cabbage. Rapid drying of the product was necessary to attain the desired quality. Drying times of from 4 to 8 hours were to be expected. The dehydrator itself was no longer the main item of equipment in the plant, as it is in a prune drying operation, but was only one link in a chain of carefully controlled and more or less highly mechanized processing steps. Multiple sets of tunnels were required to match the capacity of other units in a plant of optimum size. Adaptations of counterflow fruit drying tunnels to meet these changed conditions were accomplished successfully in a number of cases. Several important new plants built during the war employed counterflow tunnels designed specifically for vegetable dehydration.

Several different arrangements of the counterflow tunnel have been employed successfully. In most cases the so-called "twin tunnel" has appealed to designers--that is, two identical tunnels served by a single blower, heater, and recirculation return. The plan view of one such form is sketched in Figure 4. One modification of this layout, requiring less floor space, places the heater, blower, and recirculation return above the twin tunnels, which are then side by side. In a further modification this overhead space contains sheet metal flues carrying the hot flue gases from an oil-fired furnace; since the transfer of heat to the circulating air is indirect, the possibility of damaging the product with smoke or other flue gas constituents is eliminated, but at the cost of some sacrifice of heating efficiency. In a plant utilizing steam as the source of heat for the dehydrator the pipe coils or fin coils may, of course, be placed in the recirculation chamber either between or above the tunnels.

A further modification of the basic counterflow design is shown in Figure 5. Trucks are inserted through doors in the side of the tunnel, near its ends. This arrangement makes it possible to discharge the hot air from the blower and heater straight through the string of trucks, thus minimizing a condition of uneven air distribution which sometimes makes trouble in arrangements like that of Figure 4. The dehydrator design which was standard in Great Britain during the war, although a two-stage type, utilized this idea. The necessary length of the tunnel

4/ W. B. Van Arsdel. Principles of drying. AIC-300. Page 78.

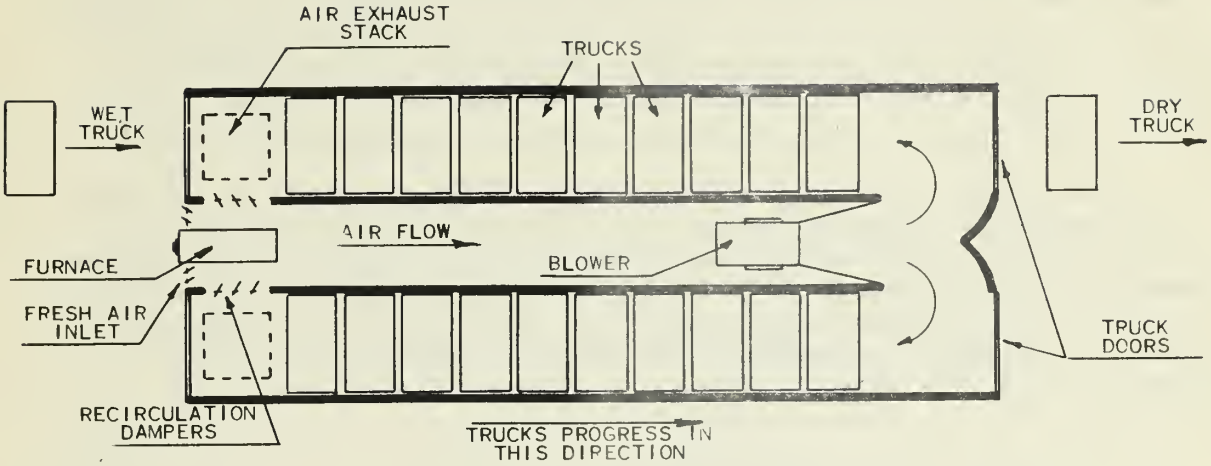


Figure 4. Direct-fired twin counterflow tunnels (plan view).

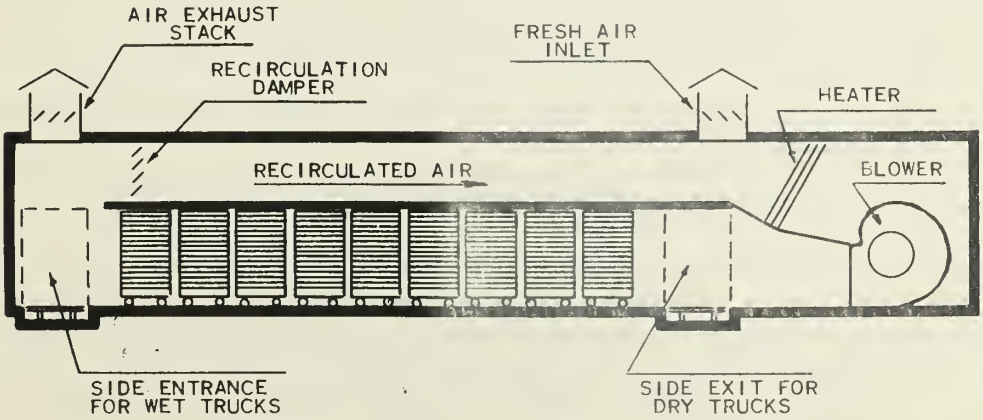


Figure 5. Side-entrance counterflow tunnel (elevation).

is, of course, increased considerably, and the side entrance for trucks both adds to the difficulty of handling trucks and further increases the floor space requirement.

Drying Characteristics of the Counterflow Tunnel. In this type of tunnel the drying air moves counter to the direction of progression of the trucks--that is, it enters at the dry end of the tunnel and is exhausted, in whole or in part, at the wet end. During its passage through the string of trucks it picks up moisture and becomes cooler;[5] thus the warmest, driest air is in contact with the nearly dry product, and the coolest, most humid air is in contact with the incoming wet material.

It is shown in AIC-300 (page 68) that for the usual conditions of commercial vegetable dehydration the fall in temperature of the air in passing from one point to another in the drying section of a continuous dehydrator is very nearly proportional to the difference in the moisture contents of the product (expressed on the dry basis) at the same two points. The formula expressing this proportionality is as follows (equation 9 in AIC-300):

$$ {}_1t_d - {}_2t_d = \pm \frac{83\ S\ L_o}{G\ \theta_h\ (T_o + 1)} (T_1 - T_2) \quad - - - - - - - \quad (1) $$

In this formula, which is only approximate, but is quite satisfactory for the calculations an operator may need to make, the plus (+) sign is used if the arrangement is parallel-flow, the minus (-) sign if the arrangement is counterflow;

- ${}_1t_d$ and ${}_2t_d$ are the air dry-bulb temperatures at points 1 and 2 respectively in the drying section;
- $T_1$ and $T_2$ are the moisture contents (dry basis) of the product at the same two points;
- S is the total area of tray surface in the dehydrator, square feet (the symbol S may be replaced by nA, A being the tray surface per truck and n the number of trucks in the drying section);
- $L_o$ is the initial tray loading, pounds of wet material per square foot of tray surface;
- G is the flow of air through the drying section, pounds of dry air per minute;
- $\theta_h$ is the total length of time, in hours, that a given truck remains within the drying section;
- $T_o$ is the initial moisture content (dry basis) of the wet material as it enters the tunnel.

Now, since we know that the rate of loss of moisture from a nearly dry product will be low, it follows from this proportionality rule that the hot air entering a counterflow tunnel will fall in temperature only slowly as it passes through a considerable part of the tunnel. From the relationship expressed in the formula above one may also see that the fall

5/ AIC-300, page 66.

in air temperature for any given degree of drying of the product will be greater the heavier the rate of loading of wet material into the tunnel, and will be smaller the greater the rate of air flow in the tunnel. To illustrate the way these relations appear in a counterflow tunnel, two examples have been calculated by the method outlined in AIC-300 (pages 77-78), one representing a relationship between rate of loading with potato half-dice and rate of air flow which uses up nearly all of the drying power of the hot air, and the other representing a relationship which leaves a considerable part of the drying power of the air unspent. The latter will be seen to be much the better way to operate the tunnel.

1. In the first example, potato half-dice (3/8" x 3/8" x 3/16") are to be loaded at $L_o$ = 3.0 pounds per square foot on trucks which carry 540 square feet of tray surface, and are to be dried to 6 percent moisture (wet basis; $T_f$ = 0.0638) in a counterflow tunnel where the wet-end air velocity between trays is 500 feet per minute, the hot-end air temperature is 150° F., and the wet-bulb temperature is maintained at 100° F. The other assumptions required in the calculation are as follows: Free cross-section area of the tunnel at its wet end, 33 square feet; initial moisture content of the prepared potato half-dice, $T_o$ = 3.40; outside air temperature 60° F., outside absolute humidity 0.0070 pound moisture per pound dry air. The number of trucks to be carried in the tunnel, the drying time, the output of dry product per hour, the total heat requirement, and curves illustrating the changes in moisture content of the material and in the dry-bulb temperature of the air as they pass through the tunnel, are to be determined. The procedure described in AIC-300, and the drying-rate nomographs for potato half-dice presented in AIC-31-VII,[6] give the moisture-content and air temperature curves shown in Figure 6, and the following other characteristics of the operation can be determined:

Number of trucks in tunnel - 7
Drying time - 13.5 hours
Output of dry product - 203 pounds per hour
Proportion of air recirculated - 0.673
Heat required per pound of water evaporated - 1622 B.t.u.
Heat required per hour - 1,030,000 B.t.u.
If the truckload of wet material enters the tunnel at a temperature of 80°, about 35 pounds of water will condense on it from the cool, moist dehydrator exhaust (the truckload will "sweat") before the material warms up to 100° and begins to dry.
Wet-bulb depression at the cool end of the tunnel - 2.5° F.

2. In the second example conditions are chosen to leave a greater unused margin of drying power in the air. The trays are loaded with 1.5 pounds of prepared potato per square foot, instead of 3.0 pounds; the air

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6/ The conditions chosen for this example go beyond the range of ordinary good practice, in that the wet-bulb depression is reduced to only 2.5° at the cool end of the tunnel. In order to make the calculations the curves given in AIC-31-VII were extended in a manner suggested by A. H. Brown, of the Western Regional Research Laboratory.

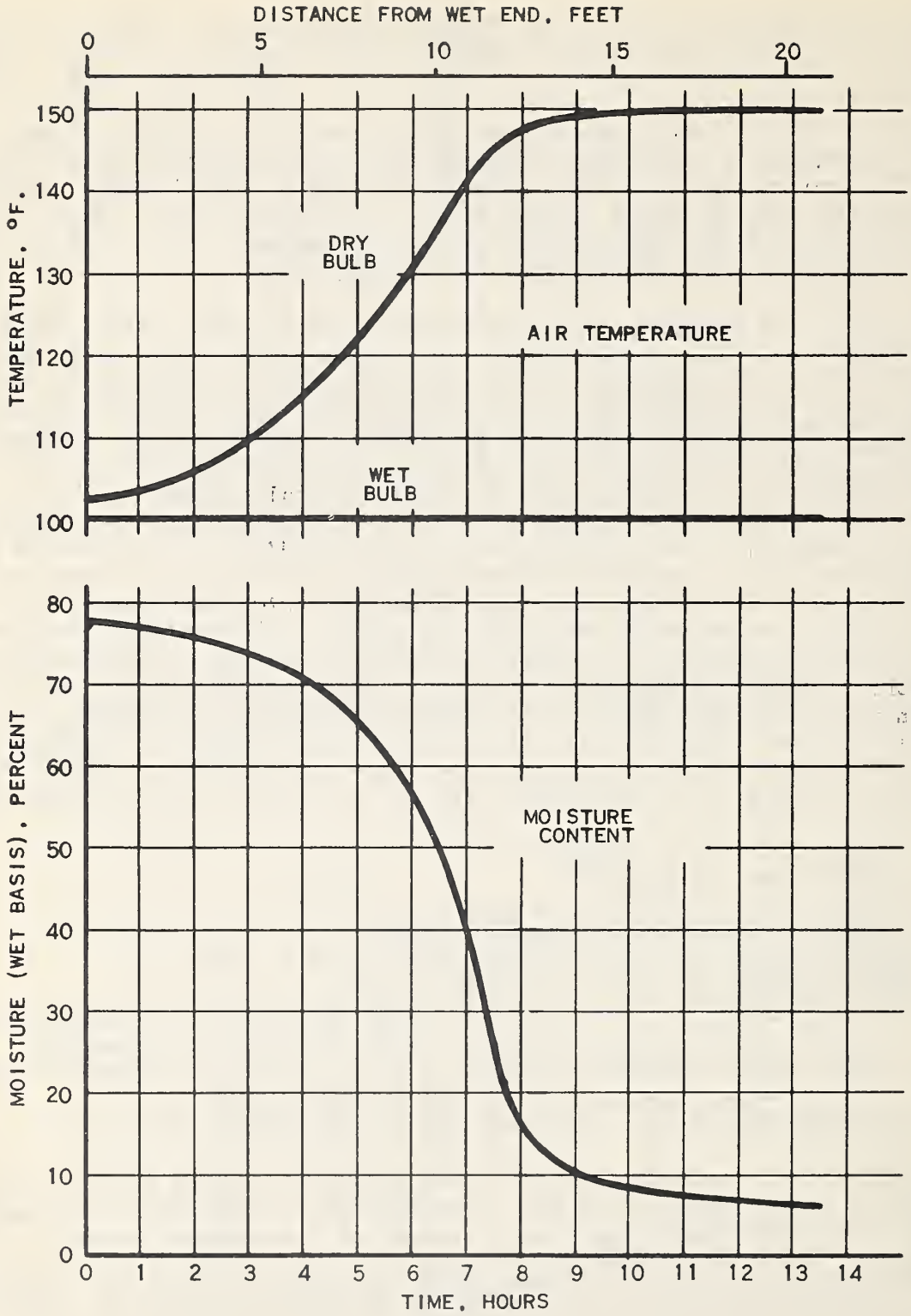


Figure 6. Air temperatures and moisture content of material in heavily loaded counterflow tunnel.

velocity is doubled; and the proportion of air recirculated is reduced until the wet-bulb temperature is only 85° F., instead of 100°. Figure 7 illustrates the changes in air temperature and material moisture content under these conditions. The other characteristics of this operation are as follows:

Number of trucks in tunnel - 12
Drying time - 7.03 hours
Output of dry product - 334 pounds per hour
Proportion of air recirculated - 0.304
Heat required per pound of water evaporated - 2380 B.t.u.
Heat required per hour - 2,490,000 B.t.u.
If the truckload of wet material enters the tunnel at a temperature of 80° F., no condensation from the exhaust air will occur; the truckload will not "sweat";
Wet-bulb depression at the cool end of the tunnel - 25° F.

Study of Examples 1 and 2 will be instructive. In the first place, note that the outcome of Example 1 would not have been any more satisfactory if a full tunnel of 12 trucks (as in Example 2) had been carried--on the contrary, the bad features would have been exaggerated; the wet-bulb depression at the cool end of the tunnel would have been only about 1°, and the drying time would have been lengthened from 13.5 hours to about 22 hours. Only a negligible increase in output of dry product would have been realized. The wet, barely warm material on the trucks near the wet end of the tunnel would certainly be ruined by bacterial growth causing souring and off flavors. Even at the 7-truck loading, Figure 6 shows that more than 6 hours will elapse before the moisture content of the material falls to 50 percent, whereas under the conditions of Example 2 this level of comparative safety will be reached in less than 1-1/2 hours. There would probably be a considerable difference in quality, in favor of the more rapidly dried product.

Comparison of Figures 6 and 7 shows that under the "heavy loading" conditions of Example 1 relatively slow drying occurs at both ends of the tunnel, while under the "light loading" conditions of Example 2 the drying starts rapidly at the wet end of the tunnel and only slows down as the material approaches dryness.

Note that "heavy loading" of a tunnel does not mean necessarily that the trays have been heavily loaded with wet material or that a large number of trucks are carried in the tunnel; rather it is such a relation between weight of water to be evaporated per hour and the temperature and mass of the air flow that the evaporative capacity of the air is nearly used up. The best single measure (in an inverse sense) of the "loading" of a tunnel is the wet-bulb depression remaining at the cool end. Practical vegetable dehydrator operators consider that a residual wet-bulb depression of at least 15 degrees is desirable; the 25° remaining under the conditions of Example 2 would not be thought extreme.

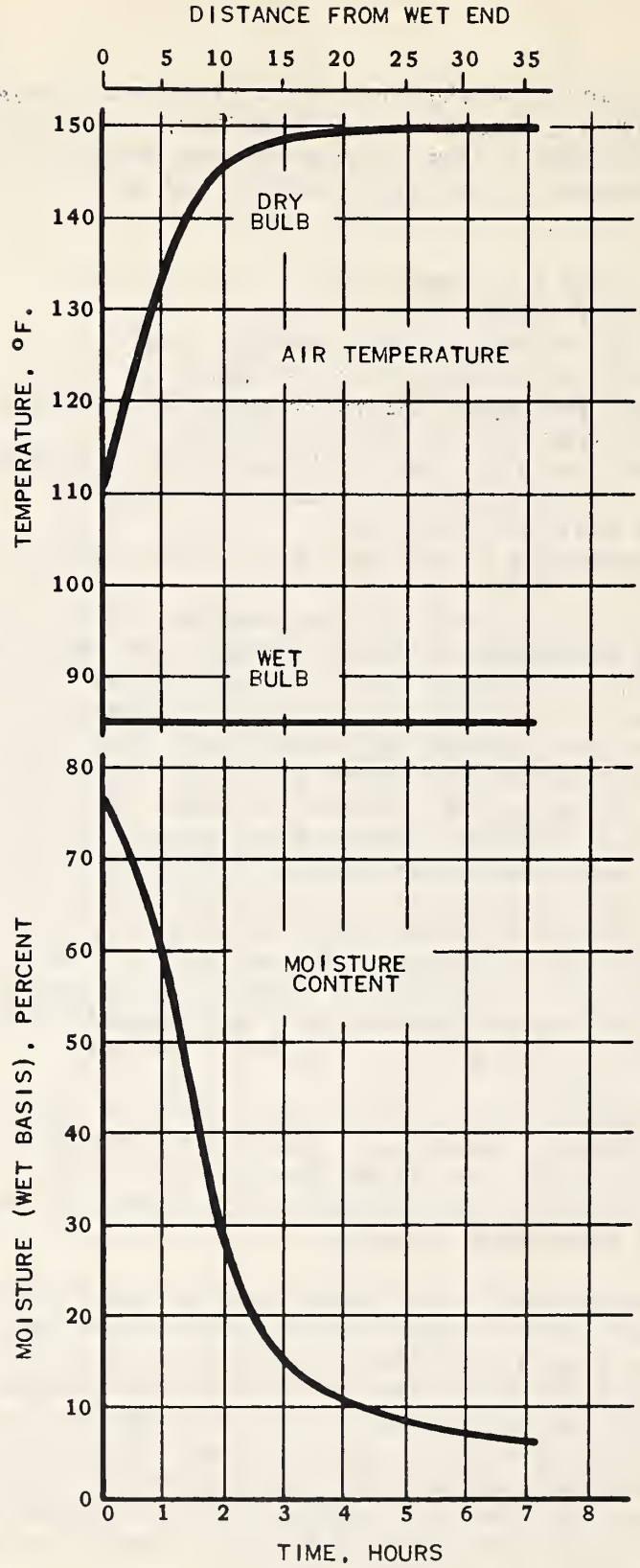


Figure 7. Air temperatures and moisture content of material in lightly loaded counterflow tunnel.

Several of the characteristics of a counterflow tunnel can be illustrated by three families of curves drawn on a single diagram, as shown by Perry and his associates.7/ Figure 8 is such a diagram calculated for the dehydration of potato half-dice in a counterflow tunnel. The coordinates are the drying time, plotted vertically, and the number of active trucks in the tunnel, plotted horizontally. Tray loading is fixed at 1.50 pounds of prepared material per square foot of tray surface; trucks contain 540 square feet of surface. The hot-end air temperature is 150°, wet-bulb temperature 85°. Air flow is 2200 pounds per minute when the velocity across trays is 1000 feet per minute, and is, of course, proportional at other velocities. The material is dried to a final moisture content of 6 percent (wet basis).

For example, if there are 10 trucks in this tunnel and the air velocity across trays is 800 feet per minute, the diagram gives an estimate of 7.1 hours drying time, 275 pounds per hour of product output, and 25° wet-bulb depression remaining at the cool end.

While the diagram only applies quantitatively to the set of conditions specified above, its general character is instructive. Increasing the number of trucks in the tunnel without changing the air velocity lengthens the drying time but increases the tunnel output. If the air velocity is increased and the number of trucks is increased at the same time just enough to keep the cool-end wet-bulb depression unchanged, two desirable things both happen--the drying time becomes shorter and the output increases. The engineer will, of course, balance these gains against the substantial increase in the power required to run the blower; doubling the air velocity without changing the number of trucks will increase the power consumption eight-fold, and if the number of trucks is increased simultaneously the increase in power consumption will be even greater.

Summary. The counterflow tunnel is characterized by having the best drying conditions at the end of the tunnel where the product is nearly dry. It can be operated in such a manner ("light loading") that reasonably good drying conditions will also prevail at the wet end of the tunnel. The maximum permissible air temperature is that which the nearly dry product will withstand without perceptible damage for a period of several hours.

## The Parallel-Flow (Concurrent) Tunnel

The thought must have occurred to most operators of counterflow tunnels, "What would happen if I loaded the fresh fruit into the hot end of the

7/ Fruit dehydration. I. Principles and equipment. R. L. Perry, E. M. Mrak, H. J. Phaff, G. L. Marsh, and C. D. Fisher. Calif. Agr. Exp. Sta. Bull. No. 698, Dec. 1946. Page 46.

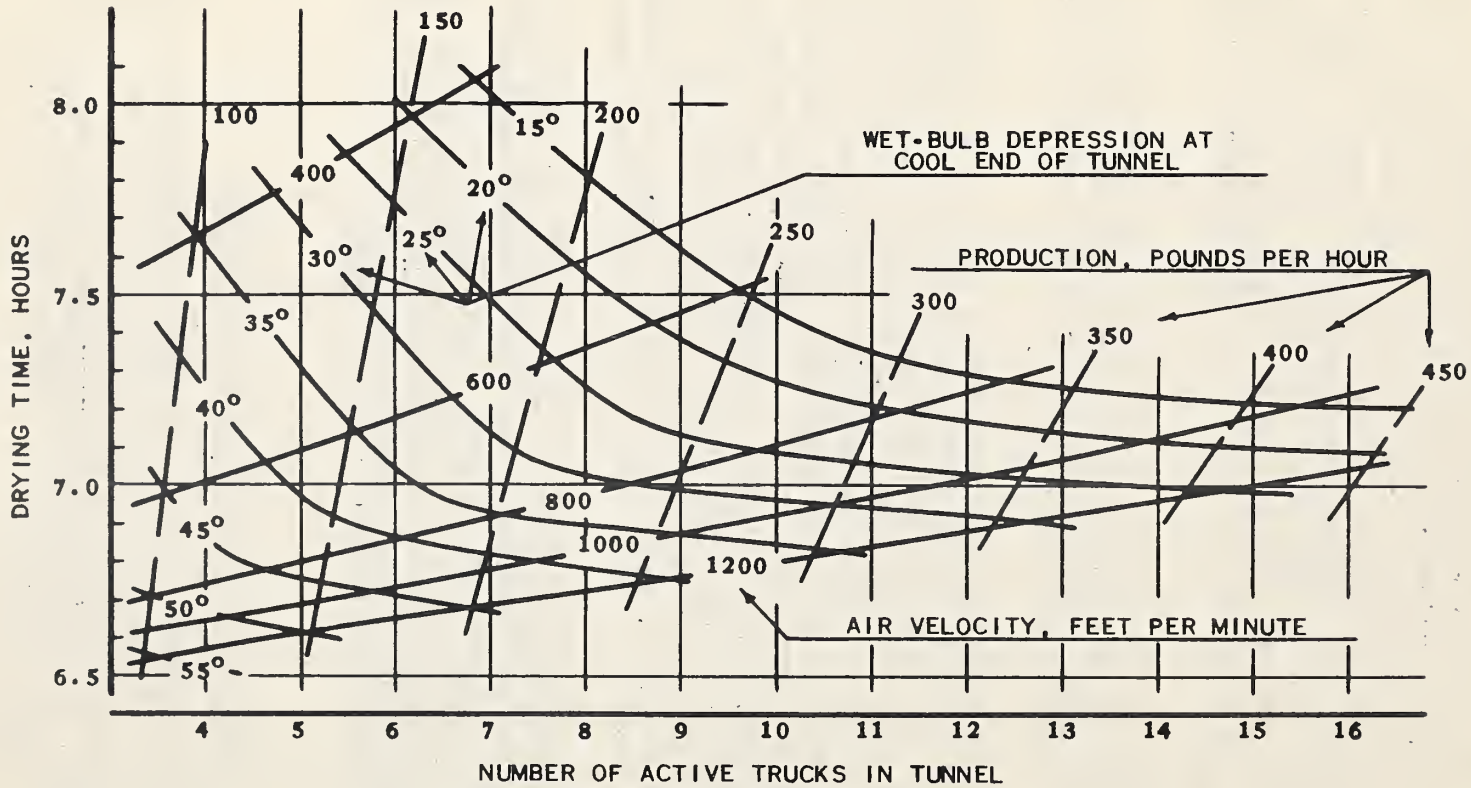


Figure 8. Relation between air velocity, number of active trucks, drying time, and product output, for a counterflow tunnel dehydrator drying potato half-dice, 3/8" x 3/8" x 3/16", to 6 percent moisture.

tunnel, instead of into the cool end?"[8] Doubtless those who tried to dry Imperial prunes that way found that while they could indeed dry the fruit, considerable bleeding and loss of juice occurred. If anyone has tried to dry prepared vegetables in a parallel-flow tunnel he probably found that his principal difficulty lay in getting the product dry enough. There are, in fact, some deep-seated differences in the behavior of parallel-flow and counterflow tunnels.

The general layout and arrangement of parallel-flow tunnels may be identical with those of counterflow tunnels, since the only difference is the interchange of product loading and unloading ends and the resulting reversal of the direction of travel of the trucks. With only these changes, Figures 4 and 5 may serve for either type.

Drying Characteristics of the Parallel-Flow Tunnel. The following example will serve to illustrate the main characteristics of parallel-flow tunnels:

3. Potato half-dice are to be dried to 6 percent moisture (wet basis) in the tunnel of Example 2 just turned around--same number of trucks, same air velocity, same hot-end temperature, same wet-bulb temperature, but loaded at the hot end instead of the cool end. How will the results compare with those of Example 2? Figure 9 shows the course of air temperatures and moisture content of material in passage through the tunnel; it is to be compared with Figure 7. The other characteristics of the two operations compare as follows:

| | Counterflow | Parallel-Flow |
|---|---|---|
| Output of dry product | 334 lbs./hr. | 203 lbs./hr. |
| Proportion air recirculated | 0.304 | 0.428 |
| Heat required per lb. evaporated | 2380 B.t.u. | 3220 B.t.u. |
| Heat required per hour | 2,490,000 B.t.u. | 2,050,000 B.t.u. |
| Wet-bulb depression at cool end | 25° | 41° |
| Drying time | 7.03 hrs. | 11.6 hrs. |

Certainly there is nothing to recommend the parallel-flow arrangement in this comparison; not only is the output cut one-third, but the efficiency of fuel utilization is less at the same time.

But the set-up of the foregoing example does not take advantage of one desirable characteristic of the parallel-flow tunnel, namely that the incoming hot air is in contact with only the very wet raw material, which will warm up only to the wet-bulb temperature of the air (AIC-300, page 28); the nearly dry product, on the other hand, is in contact with air that has already been greatly cooled. Thus the air supplied to a parallel-flow tunnel can be raised to a higher temperature than would be safe for a counterflow tunnel. Consider the following example:

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8/ The publications of the California group cited on page 3 above referred to the possible advantages of hot-end loading of fruit drying tunnels, and recognized the probable drawbacks.

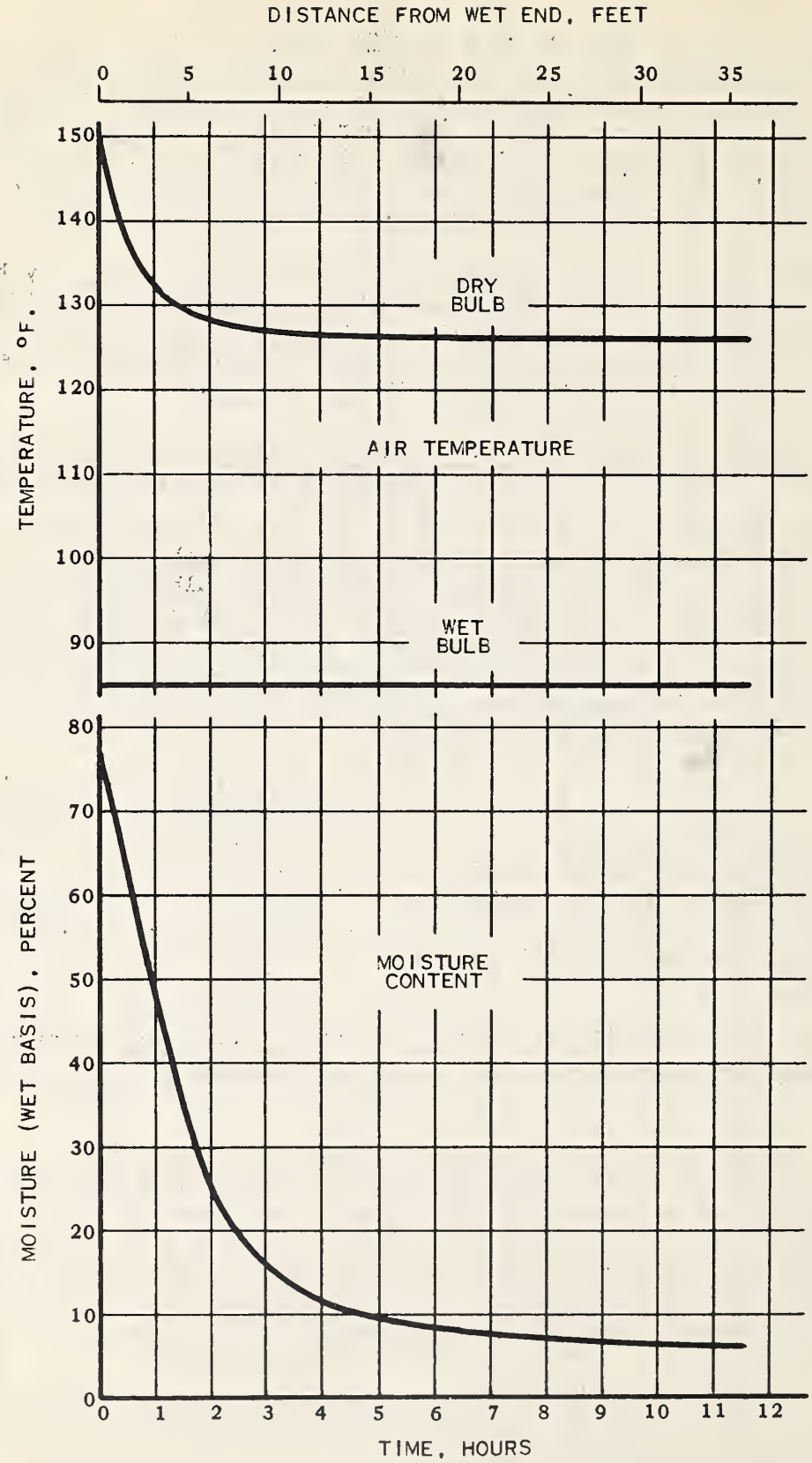



Figure 9. Air temperatures and moisture content of material in parallel-flow tunnel.

4. A parallel-flow tunnel is to dry potato half-dice to a moisture content of 6 percent (wet basis), producing 334 pounds per hour like the counterflow tunnel of Example 2. Air flow, tray loading, and number of trucks are to be the same as in that example. What combination of hot-end temperature and wet-bulb temperature will accomplish this, and what will be the other characteristics?

While there is a range of possible combinations of hot-end temperature and wet-bulb temperature which will produce the desired result, investigation by the methods already described shows that the best combination for the parallel-flow tunnel is in the neighborhood of 185° F. for the hot-end dry-bulb air temperature and 90° F. for the wet-bulb temperature. The characteristics of the counterflow and parallel-flow systems then compare as follows:

| | Counterflow | Parallel-Flow |
|---|---|---|
| Output of dry product | 334 lbs./hr. | 334 lbs./hr. |
| Proportion air recirculated | 0.304 | 0.176 |
| Heat required per lb. evaporated | 2380 B.t.u. | 3520 B.t.u. |
| Heat required per hour | 2,490,000 B.t.u. | 3,680,000 B.t.u. |
| Wet-bulb depression at cool end | 25° | 55° |
| Drying time | 7.03 hrs. | 7.03 hrs. |

So far as this comparison goes, the only disadvantage of the parallel arrangement is the relatively high heat consumption--not in itself a matter of overwhelming importance in the economics of vegetable dehydration. However, it may be stated categorically that the products made by the two systems will not be identical. One of the reasons will be apparent from Figure 10--the drying rates and temperature conditions are very different, particularly near the wet end of the tunnel. In the parallel-flow tunnel evaporation is very rapid at that end--at least 3 times as rapid as in the counterflow tunnel, even though the latter is "lightly loaded" under the conditions of Example 2; the temperature of the wet material itself will remain for a time in the neighborhood of the wet-bulb temperature (see AIC-300, page 28), that is, about 90° in the parallel-flow tunnel and 85° in the counterflow tunnel. Somewhere in the range of about 65 percent to 50 percent moisture (T = 2 to T = 1) the surfaces will begin to become relatively dry, and the material temperature will rise. During about the last half of the whole drying time the material temperature will approach the dry-bulb temperature of the air, so that the material in the counterflow tunnel will be some 3° to 4° warmer than that in the parallel-flow tunnel. These differences in history will produce differences in piece density--pieces dried in the parallel-flow tunnel will not shrink quite as much, will be somewhat more bulky than the others; there may also be differences in the extent of "heat damage" (browning), although the conditions chosen for these examples are so moderate that the browning should be insignificant in both cases. At the present time our knowledge of the effects of temperature and moisture content on rate of browning is not extensive enough to permit us to say with certainty which of these two histories would cause

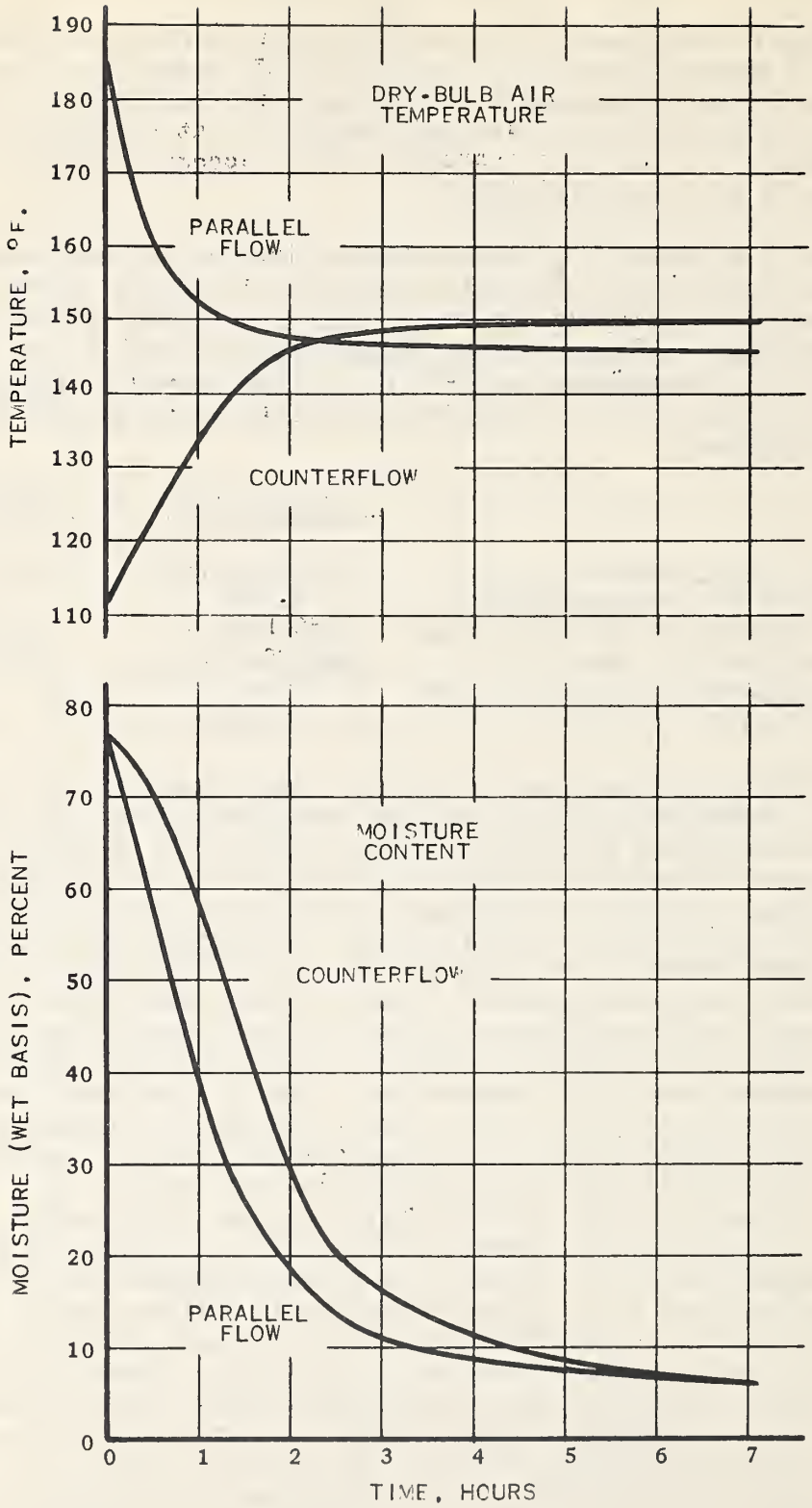



Figure 10. Air temperatures and drying curves in parallel-flow and counterflow tunnels of same dry product capacity.

the greater amount of browning. Probably a little greater degree of browning would take place in the counterflow tunnel. Another difference whose effects cannot be estimated in our present state of knowledge is the exaggerated "sawtooth effect" in the parallel-flow tunnel (see AIC-300, page 70). This is the periodic fluctuation in air temperature throughout the tunnel caused by the fact that the trucks stand still in the tunnel until the time comes for the next wet truck to be inserted; in the parallel-flow tunnel it may be reflected in a perceptible difference in moisture content between "front edges" and "back edges" of trays.

Study of the two foregoing examples shows that the parallel-flow tunnel is very effective in producing rapid initial drying of the wet material, but that its rate of drying becomes very low if the product is to be made very dry. Then suppose that we are content to produce only a partly dried product in the tunnel, and will transfer the product to some other piece of equipment for the final drying; how will the parallel-flow and counterflow arrangements compare for this special job? The following example makes such a comparison:

5. Potato half-dice are to be dried in the tunnel to only 16.7 percent moisture (wet basis; on the dry basis, $T_f = 0.20$). Air velocity in the wet end is to be approximately 1000 feet per minute (air flow G = 2200 pounds dry air per minute), tray loading $L_o = 1.5$ pounds per square foot. Temperature conditions for the two arrangements can perhaps be chosen on a basis that will be fair for both by specifying that the air temperature at the dry end of the tunnel shall fall within the range of about 140-145° F. The following results seem fairly typical of what may be expected:

| | Counterflow | Parallel-Flow |
|---|---|---|
| Number of trucks | 8 | 8 |
| Hot-end temperature | 145° F. | 220° F. |
| Cool-end temperature | 91° F. | 139° F. |
| Wet-bulb temperature | 85° F. | 100° F. |
| Proportion of air recirculated | 0.280 | 0.278 |
| Heat required per lb. evaporated | 1770 B.t.u. | 2120 B.t.u. |
| Heat required per hour | 2,560,000 B.t.u. | 4,540,000 B.t.u. |
| Drying time | 3.26 hrs. | 2.20 hrs. |
| Output of product | 542 lbs./hr. | 803 lbs./hr. |

There is thus no question that a parallel-flow tunnel of given size, operated near its temperature optimum, can turn out more partly dried potato dice (we have no reason to think the conclusion would be different for the other vegetables) than the counterflow tunnel operated in its optimum range. The hot-end temperature of 220° F. is just about the maximum that has been used in commercial operations. Again it must be pointed out, however, that the products of the two operations would be different in piece density and possibly in the extent of browning, but unfortunately we are not now in a position to say just how different they would be.

Summary. The parallel-flow tunnel is characterized by excellent drying conditions in the portion of the tunnel where the material is still very wet. However, a very dry product can be produced only if the tunnel is operated in such a manner that the heat economy is relatively poor. The evaporative cooling effect makes it possible to use a high hot-end temperature without damage to the product, and this in turn makes possible a high evaporating capacity.

## Two-Stage Tunnels

During the era of rapid expansion of the fruit drying industry in California a number of variants of the standard counterflow tunnel were designed and built. Some of these are still drying prunes successfully. Among the variants was one which might be called the "hot-center" arrangement; the single large blower discharged heated air into the center of a long tunnel, the air stream dividing and moving toward both ends. It will be seen that the wet half of this tunnel was counterflow in operation, while the dry half was parallel flow. Whatever may be the merits of this arrangement for drying prunes, no good reason for employing it in vegetable dehydration is apparent. In particular, there is ample evidence to show that vegetables are able to withstand the high wet-end temperature characteristic of a parallel-flow first stage.

The opposite arrangement, a parallel-flow wet end followed by a counterflow dry end, was first brought to public notice by C. C. Eidt, of the Canadian Department of Agriculture.9/ Such an arrangement makes possible a combination of the high wet-end evaporative capacity of a parallel-flow tunnel with the good final drying characteristics of a counterflow tunnel. This basic design became standard for most of the dehydration plants built in Great Britain and Canada during the last war, and also for a number of the new plants built in the United States.

Several different ways of realizing this type of two-stage arrangement have been used commercially. One of these, essentially a reversal of the "hot-center" prune tunnel mentioned above, and known as the "center exhaust" type, is illustrated diagrammatically in Figure 11. A single large blower, acting as an exhauster and located near the center of the long tunnel, draws heated air into both ends of the tunnel; the cooler, moisture-laden air discharged by the blower is partly exhausted and partly recirculated. An advantage of this arrangement is that the trucks are handled exactly as they would be in a simple counterflow tunnel--there is no rehandling at the transition from first to second stage. However, balancing of the air flow through the two ends and attainment of good air flow distribution through the trucks near the center of the

9/ Principles and methods involved in dehydration of apples. Canadian Dept. Agr. Publ. 625 (1938).

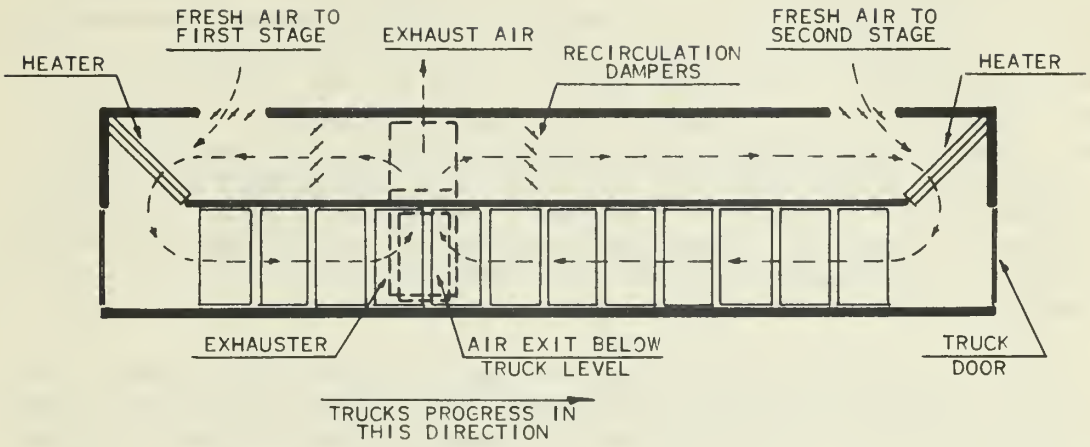



Figure 11. Center-exhaust tunnel dehydrator (plan view).

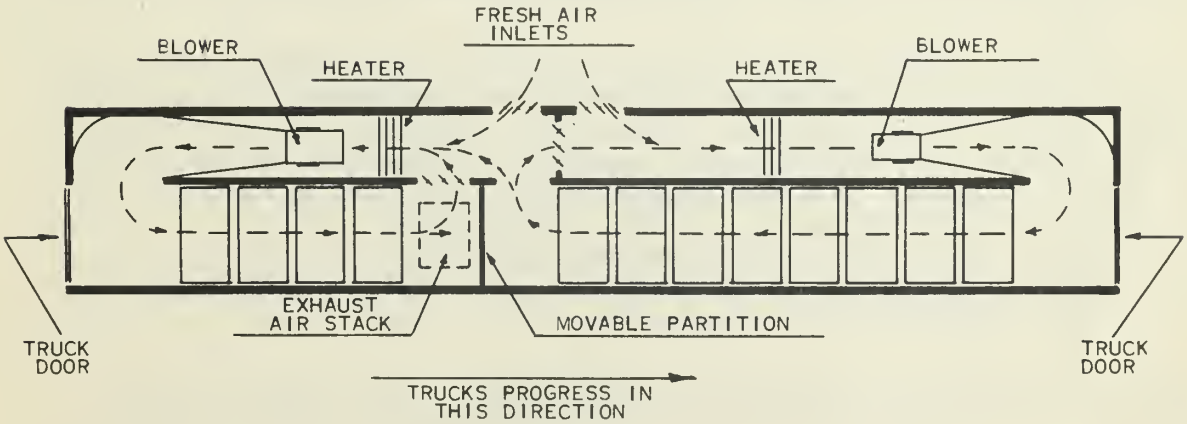



Figure 12. Two-stage single-tunnel dehydrator (plan view).

tunnel both impose serious design difficulties. So far as the writer knows, no comprehensive study of the performance of this type of tunnel has been made.

A more complex arrangement, similar in principle to the one designed by Eidt, is sketched in Figure 12. While the trucks move in a straight line through a single tunnel, the parallel-flow and counterflow sections are separated except during the movement of trucks by a sliding partition, and separate blowers and heaters are provided for the two sections. In effect, therefore, this arrangement is simply a separate counterflow tunnel placed at the end of a parallel-flow tunnel. In some versions of this design the truck-advancing mechanism is automatically synchronized with the mechanism which moves the partition between stages, so that no extra labor is required to make the transfer of trucks across the center. Dehydrators of the divided single-tunnel type have been used successfully in a considerable number of plants.

The two-stage arrangement which has been most widely used separates the two stages completely, manual handling being required to transfer trucks from the "dry end" of the parallel-flow tunnel to the "wet end" of the counterflow tunnel. Both stages may follow quite conventional designs, except that blower and heater capacities will be adjusted to be appropriate to the two quite different functions of the two stages--the parallel-flow section to accomplish a great deal of evaporation quite rapidly, and the counterflow section to maintain good finishing conditions with little evaporative load. Since it is desirable to use the exhaust air from the counterflow section, still warm and relatively dry, as at least a part of the "fresh" air supply to the parallel-flow section, ductwork of fairly large dimensions is required between the two stages if the tunnels are physically separated.

The arrangement which was preferred in most of the dehydrators of this type built in the United States during the last war provided, in effect, straight-through handling of the trucks from a bank of parallel-flow primary tunnels to a bank of counterflow secondary tunnels, as sketched in Figure 13.

The arrangement which became standard in Great Britain,[10] on the other hand, as sketched in Figure 14, placed primary and secondary stages of equal length side by side, the direction of progression of the trucks being reversed after the transfer from the parallel-flow tunnel to the counterflow tunnel. Thus wet trucks were inserted and dry trucks were withdrawn at the same end of a group of dehydrators, resulting in a quite different pattern of truck traffic between the truck loading point, the dehydrators, and the truck unloading point than was appropriate for an arrangement like that of Figure 13.

Drying Characteristics of the Two-Stage Tunnel. The combination of parallel-flow primary stage and counterflow secondary stage possesses

10/ "Vegetable Dehydration". British Ministry of Foods, London (1946).

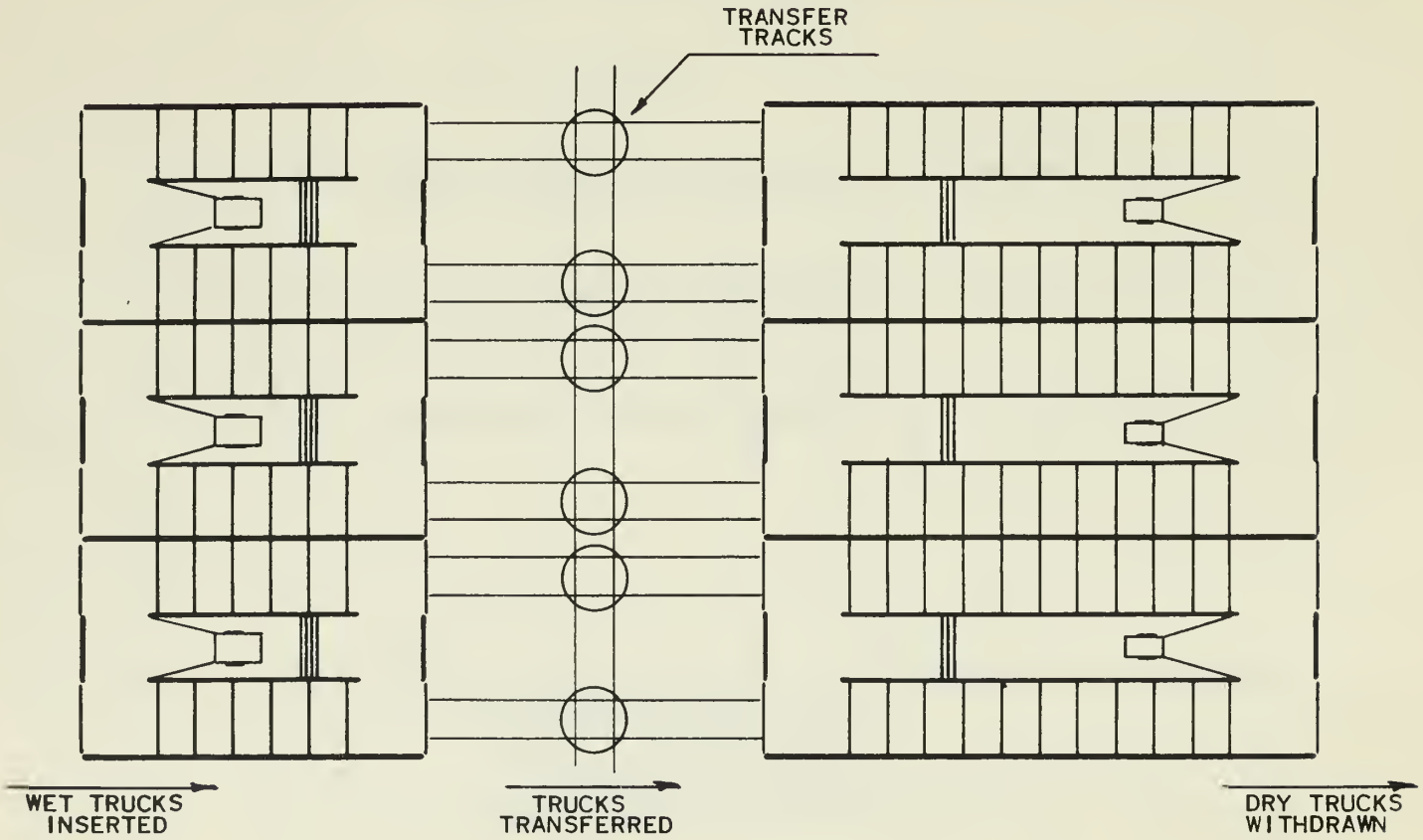
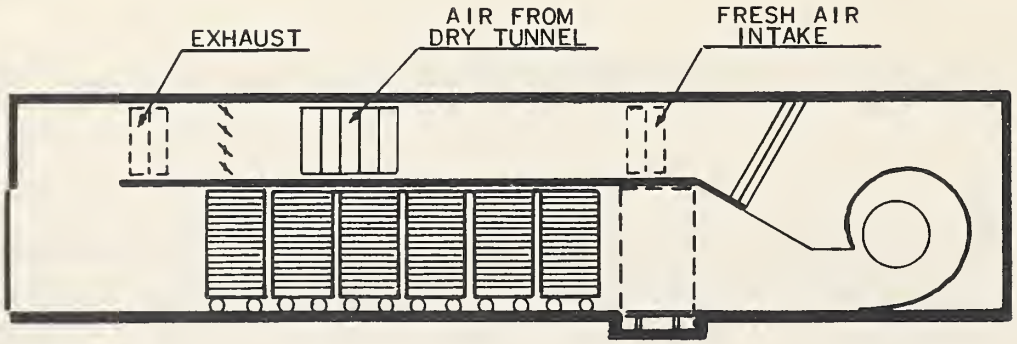
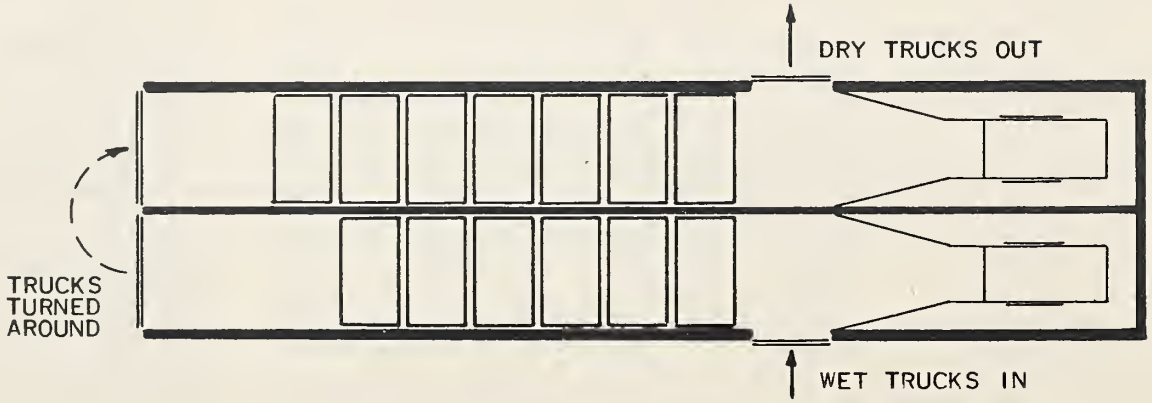



Figure 13. Separate banks of parallel-flow and counterflow tunnels.




Vertical Section through Wet Tunnel




Horizontal Section through Truck Level

Figure 14. Primary and secondary stages side by side. (Type standardized by British Ministry of Foods)

some distinctive characteristics, with which the operator of such a system should become familiar. Each stage, considered by itself, behaves like its simple prototype; but when the two stages must act together as a single drying unit, each has an effect on the operation of the other.

Example 5 of the preceding section of this bulletin may easily be extended to provide an example of a two-stage system, as follows:

6. The 803 pounds per hour of potato half-dice dried in the parallel-flow tunnel of Example 5 (page 17) to a moisture content of 16.7 percent (wet basis; dry basis T = 0.20), is to be finally dried to 6.0 percent moisture (T = 0.064) in a counterflow second-stage tunnel. The latter is to be operated with a hot-end temperature not over 150° F., air flow through the drying section is to be 2200 pounds of dry air per minute (equal to the flow in the primary stage[11]), and all of the exhaust air is to be used as the "fresh air" makeup in the primary stage. Then in order to make the air flows in the two stages balance, the proportion of recirculation must be the same in both. In order to balance the flow of product through the primary stage, trucks must move into the counterflow side at the same rate that they leave the primary, that is, one every 2.20/8, or 0.275 hour (16.5 minutes). By use of the methods of estimation already described, it is found that the two separate sections and the combined two-stage unit have the following characteristics:

| | Primary Stage | Secondary Stage | Combined Unit |
|---|---|---|---|
| Number of trucks | 8 | 16 | 24 |
| Hot-end temperature | 220° F. | 147° F. | |
| Cool-end temperature | 139° F. | 143.6° F. | |
| Wet-bulb temperature | 100° F. | 81° F. | |
| Propor. recirculation | 0.269 | 0.269 | |
| Heat per lb. evap. | 1200 B.t.u. | 23,800 B.t.u. | 2110 B.t.u. |
| Heat input per hour | 2,560,000 B.t.u. | 2,140,000 B.t.u. | 4,700,000 B.t.u. |
| Drying time | 2.20 hrs. | 4.40 hrs. | 6.60 hrs. |
| Output of 6% product | | 712 lbs./hr. | 712 lbs./hr. |

Figure 15 shows the course of moisture content and air temperatures through this combined unit. The nearly constant air temperature throughout the whole counterflow stage is striking. The apparent high heat usage per pound of water evaporated in this stage is really not significant, because the unused heat adds to the heat supply of the primary stage; the combined heat usage of the two stages is only moderate.

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11/ Equality of air flows in the two stages, as chosen for this example, is not a necessary condition. However, it is within the range of common practice, especially if the secondary stage is divided as suggested in the second paragraph following this. When the secondary is a single tunnel, as illustrated in Figures 11, 12, 13, and 14, a somewhat lower air flow is commonly used than in the primary stage.

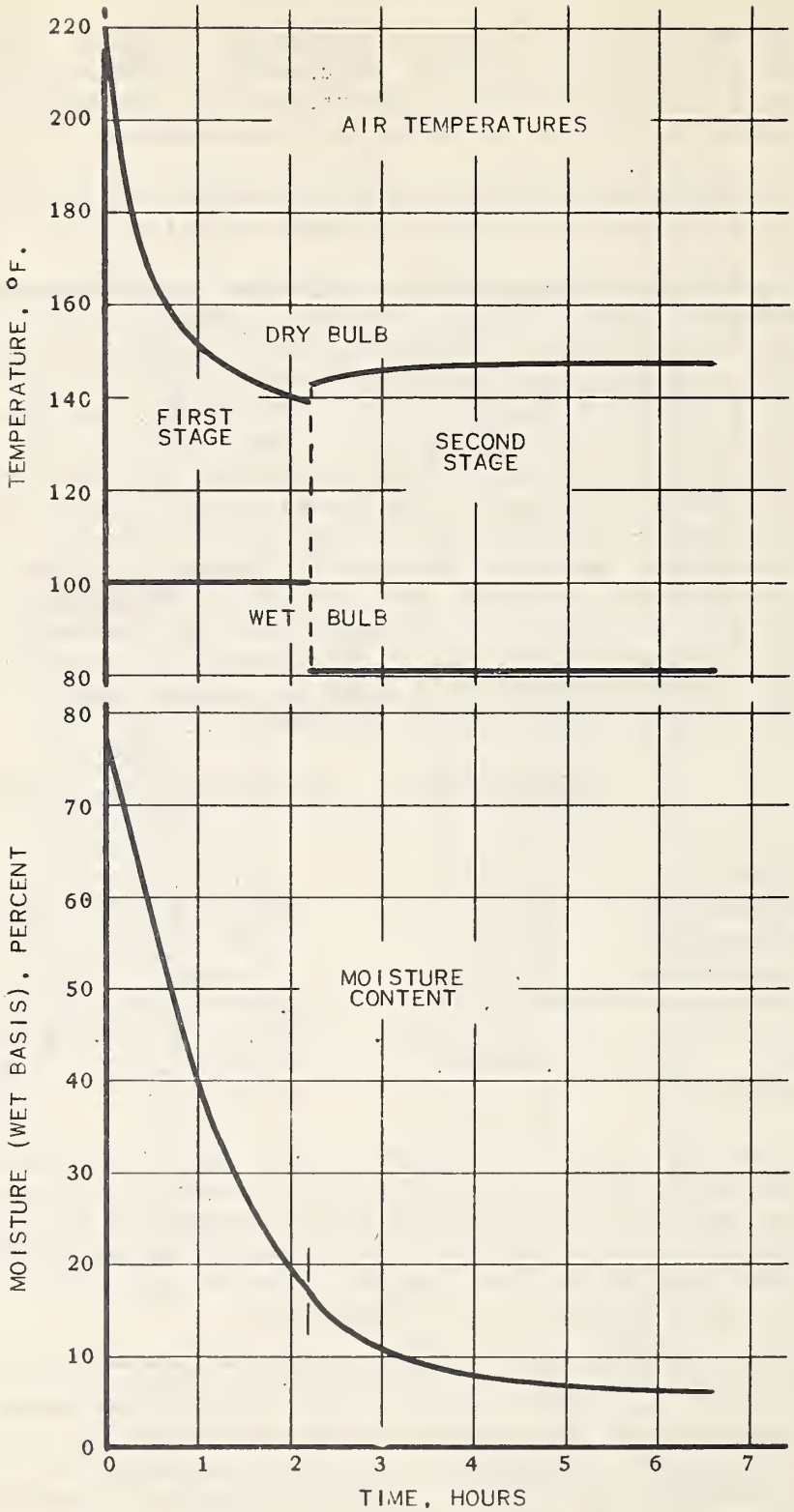


Figure 15. Air temperatures and moisture content of material in a two-stage tunnel.

It may be noted that so far as drying time and heat economy are concerned, it is immaterial whether this counterflow secondary stage is constructed as a single 16-truck tunnel or two 8-truck tunnels with the air flow divided between them. The fan power required would be substantially less in the latter arrangement, which has been used successfully in several commercial installations.

It may be of interest to compare the characteristics of this two-stage combination with a pair of counterflow tunnels such as those of Example 2:

| | Two-stage Unit | Two Counterflow Tunnels |
|---|---|---|
| Number of trucks | 24 | 24 |
| Drying time | 6.60 hrs. | 7.03 hrs. |
| Output of dry product | 712 lbs./hr. | 668 lbs./hr. |
| Heat per lb. evaporated | 2110 B.t.u. | 2380 B.t.u. |
| Heat input per hour | 4,700,000 B.t.u. | 4,980,000 B.t.u. |

The two different kinds of arrangement would occupy substantially the same floor space. The two-stage unit realizes somewhat more rapid drying and a correspondingly higher output of dry product, with somewhat better heat economy than the simple counterflow unit. Against these advantages for the two-stage unit must be set some increase in the capital cost of the dehydrator, increased labor cost unless the truck transfer between stages is handled automatically (with a further increase in capital cost), and a more complex control problem. Product made in the two-stage unit will tend to be more bulky than that made in a counterflow dehydrator. A rough estimate of the way the material temperature itself changes during its passage through the dehydrator indicates that the two-stage tunnel of the above example would warm the material to a somewhat higher temperature than the counterflow tunnel during early stages of drying, but that the material in the counterflow tunnel would be a few degrees the warmer during the last two-thirds or more of the entire drying time. Under these conditions the counterflow tunnel would be expected to cause a little greater degree of browning, or scorching, than the two-stage tunnel (probably inappreciable in both kinds of tunnel for the conditions of the above example, provided the potato were sulfited or very low in sugar content).

In the above example of a two-stage tunnel more than 95 percent of the evaporation of water took place in the first stage. Toward the end of this stage the temperature of the air had fallen so far that the drying rate of the material was decreasing rapidly. At the point of transfer to the "cool end" of the counterflow second stage air of somewhat higher temperature and materially greater wet-bulb depression was encountered, and the drying rate of the material increased noticeably. It can be shown that the shortest total drying time in a two-stage tunnel will be realized, other conditions remaining the same, if the transition from first to second stage is made at such a point that the drying rate of the material just after the transition will remain the same as it was just

before the transition. Roughly, this will also be the point where the wet-bulb depressions of the two streams of air leaving the two stages will be equal. Under the conditions of the example, the combination resulting in the shortest drying time (and therefore highest output) would comprise only 3 trucks in the primary tunnel, 21 in the secondary. Drying time would be reduced from 6.60 to 6.46 hours, output increased from 712 pounds per hour to 728 pounds. The heat economy would be slightly poorer. Thus there would be little to gain by changing to the much shorter primary tunnel; on the contrary, the design and satisfactory operation of such a short tunnel would be difficult. The ratio between lengths of the secondary and primary stages has ranged between 1-1 and about 3-1 in the practical two-stage tunnels which have been in successful commercial operation.

The performance of the British two-stage tunnels has been quite completely described in the bulletin, "Vegetable Dehydration", published by the Ministry of Foods in 1946. These dehydrators were designed to handle white potatoes, carrots, or cabbage. Trucks carried two stacks of 50 trays, each of 8 square feet area--800 square feet per truck. Normally 6 trucks were carried in the primary stage, 7 trucks in the secondary. Blower discharge was about 45,000 cubic feet per minute in the primary, 35,000 c.f.m. in the secondary; heating was by means of banks of finned steam pipes on the suction side of the blowers. Controllable recirculation was provided in both stages. Exhaust from the secondary stage normally furnished the entire "fresh air" supply of the primary.

Data are given in the bulletin on plant experience in the drying of all three vegetables. White potatoes were strip-cut, 3/16" x 5/16" in cross-section. After blanching, 13 pounds of strips were loaded on each tray (1.63 pounds per square foot); initial moisture content was about 80 percent (wet basis), final moisture content 7-8 percent, drying ratio 5.2 to 1. Hot-end temperature in the primary tunnel averaged 213°, wet-bulb temperature 114°, exhaust air temperature varying from 144° directly after insertion of a wet truck to 154° just before inserting another (the "sawtooth effect"); hot-end temperature in the secondary stage was 157°, wet-bulb temperature 92°. Average moisture content of material leaving the primary stage was 30 percent, but, as is usual in a parallel-flow tunnel, the moisture content of the material at the downstream edge of the trays was about 10 percent higher than at the upstream edge; the reversal of air flow in the secondary reduced this difference between front and back edges to less than 1 percent. Mean total retention time in both stages was 6.5 hours, but during a total of 0.5 hour of this the blowers were shut down during the movement of trucks. Output of dry product was approximately 500 pounds per hour.

The dehydrators had been designed on the assumption that 82 percent of the total evaporation would occur in the primary stage; actually, as the above data show, about 91 percent of the total took place in that stage. The following derived estimates may be of interest as a rough check on the methods of calculation described in AIC-300:

The humid volume of air at the hot end of the primary stage is 18.2 cubic feet per pound dry air; mass flow of air in that stage is therefore 2470 pounds dry air per minute. The mean rate of evaporation in the whole tunnel during the period while the fan is running is 2280 pounds of water per hour, 2070 pounds of which is evaporated in the primary tunnel. The mean rise in absolute humidity of the air is therefore 0.0139 pound of water vapor per pound dry air, corresponding (according to the rule used in AIC-300) to a fall in air temperature of about 70°--that is, from 213° to 143°. The observed exhaust temperature, according to the reports, varied from 144° just after the introduction of a wet truck to 154° at the end of a truck cycle; thus the fall in air temperature corresponding to a rise of 0.001 in absolute humidity ranged from 4.2° to 5.0°, averaging about 4.6°. The figure of 5° suggested in AIC-300 allows for somewhat larger heat losses than were actually encountered in these British dehydrators. The calculated absolute humidity at the exhaust, 0.0569, corresponds to a wet-bulb temperature of 113° at an exhaust temperature of 144°, 114° at an exhaust temperature of 154°--a fall of 1° in wet-bulb temperature at the beginning of each truck cycle, and no appreciable fall at the end of the cycle.

At least one commercial plant has used three-stage tunnels successfully. The major advantage of such an arrangement probably is its flexibility with respect to the drying of a wide variety of different products under nearly optimum conditions for each. More labor is required to operate it unless truck handling is completely automatic; control is also more complex than in the simpler arrangements.

The air temperature in the counterflow second stage of the example on page 23 changed so little (less than 4° F.) and the humidity rose so little (about 1 percent) that evidently it would have made little difference to the theoretical performance of the combined unit if this second stage had been arranged for parallel flow. Nevertheless, there is a real advantage in the reversal of air direction; as has been noted above, a parallel-flow tunnel is likely to produce trayloads which are appreciably drier near the leading edge than near the trailing edge, and the reversal of air flow partway through the tunnel will even out this difference. This might, of course, be accomplished by reversing the layout of a parallel-flow secondary stage with respect to the primary, as well as by using a counterflow secondary.

The techniques of operating a multi-stage tunnel, and of starting it up and shutting it down, are rather more complex than those which are satisfactory for a counterflow tunnel. They will be discussed fully in another bulletin of this series.

Summary. The combination of a parallel-flow first stage tunnel and a counterflow second-stage tunnel produces good drying conditions at both ends of the dehydrator, and makes possible a shortening of the drying time and corresponding increase in output for a dehydrator of given size. From the practical standpoint this increase in output may be at least in part offset by the higher initial cost and higher operating cost as compared with a well designed counterflow dehydrator.

## The Combination Compartment and Tunnel

The characteristic feature of this class of dehydrator is the back-and-forth transverse flow of air through the trucks. A simple form was sketched in Figure 3 (page 2). Scores of different modifications of the basic idea have been proposed, many of them in the patent literature. Comparatively few of them have, however, been used for commercial vegetable dehydration.

A feature common to most of the commercial compartment tunnels is the provision of an auxiliary controllable air reheater at each compartment--that is, at each truck position. In addition, a booster blower and controllable recirculation are usually provided at each compartment. The multiplicity of independent controls makes such a drier extremely flexible; almost any desired kind of temperature-humidity history can be imposed on the material as it passes through the tunnel. For this reason the design has merit as a general-purpose experimental continuous drier. An experimental drier of this type has been used at the Western Regional Research Laboratory to produce relatively large quantities of dehydrated vegetables dried according to various systems; for example, it is possible to set the compartment temperature and humidity controls in such a manner that each truckload of material passing through the unit will experience conditions characteristic of a counterflow tunnel or of various two-stage combinations. If only a small quantity of material is needed, a cabinet drier with proper controls will accomplish the same purpose.

Unless a compartment tunnel is designed and constructed with the greatest care, serious operating difficulties may be encountered. The most common difficulty is a result of insufficient provision for straightening out and equalizing the air flow through the trucks. Air forced to make a sharp turn tends, like any moving body, to hug the outside of the curve. Control of this tendency in a high velocity air stream turned through 180° is well nigh impossible by means of any ordinary system of "splitters" or guide-vanes. Systems of orifice plates or nozzles have been used with some success, but at the cost of a substantial increase in the power required to move the air. Another difficulty that will be encountered in a poorly designed compartment tunnel is the short-circuiting of air directly from one compartment to the next, without passing through a truck; a substantially tight seal of the truck ends against the tunnel walls is required.

Only one general statement can be made about the drying characteristics of a compartment tunnel equipped with auxiliary heaters; the wet-bulb temperature of the air (as well as the dry-bulb temperature) will rise at each passage through a heater. Thus, if the general air circulation through the drier is counterflow to the direction of movement of the trucks, the wet-bulb temperature will be progressively higher from the dry end to the wet end of the unit unless additional fresh air is introduced at each stage. This contrasts, of course, with the behavior of the simple counterflow tunnel, in which the wet-bulb temperature is substantially

constant from one end to the other.[12] Other drying characteristics of the compartment tunnel are quite completely within the control of the operator if, as is usual, the auxiliary heaters are individually controllable. This fact makes it theoretically possible to set up a gradation of temperatures along the tunnel which will produce the highest realizable output of acceptable product.

The writer has observed that the basic idea of the compartment tunnel seems inevitably to appeal to every engineer who is introduced to dehydrator design. Some successful examples of the type have been operated. On the whole, however, the commercial fruit and vegetable dehydration industry has favored the counterflow and two-stage arrangements described above, because of their simplicity and relative freedom from the difficulties inherent in the compartment arrangement.

## Other Tunnel Arrangements

Two additional possibilities in tunnel arrangement may be noted briefly. Both have received at least pilot-plant study, but apparently neither has gone into commercial operation.

One is a closed-cycle system. That is, there is no exhaust to the atmosphere; instead, the exhaust air from the dehydrator is partially dehumidified (for example by passage through a water spray tower in which its dew point will be lowered) and returned to the fresh air intake. The system has been proposed for onion and garlic dehydration, in order to diminish the nuisance aspect of the highly odorous exhaust. It has also been investigated as a part of a system for dehydrating food products in an atmosphere of oxygen-free gas, the closed cycle being necessary to keep the usage of fresh gas to a minimum.

The other arrangement consists essentially of a single separate compartment at the wet end of a tunnel, and arrangements for controlling temperature and humidity in the compartment to bring about the blanching of the prepared vegetable, possibly combined with a beginning of rapid drying. Blanching (which is discussed fully in another bulletin of this series) is a preliminary heat treatment of cut vegetables found to be necessary to attain good keeping quality and easy rehydration; it involves raising the temperature of the material to from 180° to 210° F. for a period of from 1 to several minutes, and is usually accomplished by exposure to steam or hot water. But either steam or hot water leaches some of the soluble nutrients from the material, and must therefore be regarded as something less than ideal for blanching. It would theoretically be

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12/ As will be evident, if an experimental compartment drier is to be used to simulate the behavior of a simple tunnel, this constancy of wet-bulb temperature can be realized only by making each compartment independent of the others, with its own control of recirculation and of fresh air intake and exhaust.

possible to expose a truckload of material in the blanching compartment to a current of air of carefully controlled rising temperature and humidity, so that neither drying of the material[13] nor condensation on it would occur; within a few minutes the wet-bulb temperature of the circulating air and the temperature of the material could be raised to the desired blanching temperature, say 180°, and the material temperature could be held there for the desired length of time. Then the wet-bulb temperature of the air could be lowered quickly and rapid drying would begin. In due course the truck would enter the tunnel and go through the remainder of the drying cycle. Investigators in several countries, including the United States, have experimented on a pilot scale with this interesting idea. Little has been published about it, but informal reports have indicated that control is difficult. The margin between condensation and excessive and premature drying, even scorching, at the high temperatures in question is narrow. Possible advantages in the method are great enough, however, to warrant the expectation that further attempts will be made to develop a practical procedure. A complicating factor is the present practice in many plants of introducing a required concentration of sulfite into the product by means of a spray of sulfite solution in the course of or following the blanching step.

## ACKNOWLEDGMENTS

The ideas set forth in this bulletin have developed during a period of ten years. The author regrets deeply that he cannot give due credit to all the colleagues in the Western Regional Research Laboratory, the research people in other institutions, and engineers and operating men in the dehydration industry who have helped to form these ideas. His special thanks, however, are extended to the following reviewers of the manuscript for the valuable suggestions they have made: N. C. Aceto and R. K. Eskew of the Eastern Regional Research Laboratory, W. D. Ramage, A. H. Brown, E. Lowe, H. S. Olcott, H. K. Burr, C. E. Hendel, R. R. Legault, and B. Makower of the Western Regional Research Laboratory, and Professor R. L. Perry of the Davis campus of the University of California.

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13/ The desirable effects of blanching are apparently difficult to produce in a partly dried material.